LIFE CYCLE ASSESSMENT OF A HEMP CONCRETE WALL: IMPACT OF THICKNESS AND COATING.

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Abstract

In a context of sustainable development and energy sparing, a life cycle assessment (LCA) may be useful to make good choices. Thus, this study concerns the LCA of an environmentally friendly material used for building construction, hemp concrete. The functional unit is first defined per square such that the wall may provide the function of bearing wall meter and its thermal performance is described by a thermal resistance of 2.78 m².K/W. The results then showed that the production phase of raw materials is mainly responsible for the environmental impact of the wall, mostly due to the binder production. It was also shown that, compared to traditional construction materials, hemp concrete has a low impact on environment. Moreover, hemp concrete contributes to reduce climate change as photosynthesis-mediated carbon sequestration and carbonation serve to reduce atmospheric carbon dioxide. A sensitivity analysis is performed on three criteria: wall thickness, renewal of coatings and compounds of the indoor coating. Our results show that environmental indicators evolve with wall thickness, except for the climate change indicator. It improves with thickness due to carbon sequestration and carbonation. Moreover the increase in the wall's thermal resistance with wall thickness is not taken into account in such an LCA performed at the material level. The renewal of coating slightly impacts the environmental indicator for small numbers

of renewals but it leads to negative effects if they are too numerous. It appears that hemp-lime coating has a greater impact than sand-lime coating as it embeds more binder.

Keywords: bio-based material, environmental impact indicators, carbon uptake, sprayed hemp concrete, wood framework.

1 Introduction

In a context of sustainable development, one of the objectives is to reduce the environmental impact of human activities. Life cycle analyses or assessments are scientific studies that assess the environmental impact of products, processes or activities from cradle to grave [1][2]. These investigations also allow the identification of environmentally preferable solutions. It is emphasized that such studies may lead to more or less scattered results in relation with value judgments, assumptions, boundary conditions, scenarios and databases [3]. In order to avoid disparity, international standardisations, such as ISO 14040, have emerged [4][5]. Initially developed for industrial products, LCA methodology is now used in the building sector. In Europe, the technical committee CEN/TC 350 has developed standards in order to harmonise the creation of Environmental Product Declarations (EPD) for building products and materials. The recent publication of EN 15804 [6] provides the core rules for that. This standard will progressively replace national ones like the French NF P 01-010 [7] standard.

Whole building LCA should take into account the impact linked to the construction phase, use phase and the end-of-life of buildings. Several assessment tools have been developed at the whole building and product levels [8]. They can be used as decision support [9].

Compared with industrial products, buildings show several features. Firstly, buildings are unique (shell, systems and location) and locally assembled. Local climate influences their energy needs. Moreover, the energy mix is also dependent on the location [10][11]. Secondly, several materials can be used, associated with various production processes. This requires large databases of materials such as Ecoinvent [12], BEES[13], CRTI[14], GaBi LCA database [15], etc. Lastly, buildings show long lifespans, with building retrofitting and, sometimes, multiple functions. The usually encountered lifespan is from 30 to 100 years [16][17].

Throughout the life cycle (LC), numerous studies have shown that the use phase is the most harmful one. Furthermore, the demolition and recycling of materials are rarely addressed in LCA. Ramesh et al. drew up an overview of 73 studies, including both residential and commercial buildings from 13 countries [18]. They concluded that 80 to 90% of the effects are linked to the operating phase, whereas only 10 to 20% are embedded impacts. The review by Rossi et al. [10] shows that the operation phase accounts for 62 to 98% of total life cycle impact, while the construction phase accounts for 1 to 20% and the dismantling phase for 0.2 to 5%. Lastly, according to Van Ooteeghem and Xu [19], the operating energy and global warming potential (GWP) is responsible for 90% of the total energy and GWP after 50 years for retail buildings in Canada.

In order to reduce the environmental impact of buildings, one approach consists in reducing fluxes. From a thermal point of view, this can be achieved by increasing insulation, leading to very low or zero-energy buildings. In such cases, the non-operational phase is more significant and green materials exhibit greatest interest. Actually comparisons of concrete-based and wood framework buildings, with similar insulation levels, show that wood-based buildings lead to lower embedded energy and CO_2 emission than concrete ones [11][16][17][20]. Similar conclusions are obtained comparing wood products with usual building materials such as brick, glass fibre insulation and extruded polystyrene in [21]. Furthermore, carbon sequestration during growth (photosynthesis) is allocated as negative emission.

Through this literature review, the use of environmentally friendly materials with good insulation properties appears as a good means of reducing the environmental impact of buildings. Among such materials, hemp concrete is a bio-based building material. Its hygrothermal behaviour reduces energy needs while maintaining high indoor comfort. Its thermal conductivity is approximately 0.1 $W.m^{-1}.K^{-1}$ [22], its water vapour permeability is approximately 3.2 10^{-11} $kg.m^{-1}.s^{-1}.Pa^{-1}$ at low and medium relative humidity, and its moisture buffer value is 2.15 g/(m².%HR) [23].

Assessments of the lifecycle impact of hemp concrete wall were carried out by Boutin et al. [24] and by Ip and Miller [25]. In both cases, the hemp concrete is shuttered and the timber frame is taken into account. The lifetime is over 100 years. These studies differ from the composition of the wall (density of hemp concrete, thickness, wood frame) and from conditions and practices (France and UK). The results lead to similar conclusions, they show that hemp concrete has a positive impact on the environment as it allows carbon sequestration (according to Ip and Miller: 82.71 kg $CO_{2eq.}$ per square metre of wall). A further study, performed by Ip and Miller, includes rendering but excludes the maintenance of the wall. With rendering, the wall can still sequester carbon.

The aim of this study is to perform a Life Cycle Assessment (LCA) from cradle-to-grave of a sprayed hemp concrete wall. It includes hemp concrete, wood frame and rendering. A sensitivity analysis is performed on the thickness of hemp concrete, the renewal of coating and the composition of coating. It allows comparisons with other insulation practice, identifies the main impacts of a hemp concrete wall and concludes with guidelines for improving this product by reducing these impacts throughout the life cycle. Moreover, the results, presented similarly to an Environmental Product Declaration, can be used as an LCA database at the building level. This study was conducted according to the ISO 14040 series of life cycle assessment standards [4] and to the French NF P 01-010 standard concerning environmental impacts of building products [7]. It was performed on the basis of excel sheets.

The materials and the functional unit are first presented. Then, the system boundaries and the stages related to the production of the components of the functional unit (hemp, lime, wood frame, coating), the implementation and the end-of-life are described. Finally, environmental impact indicators are established for the functional unit and a sensitivity analysis is performed on the wall thickness, on the composition and on the renewal of coating.

2 Presentation of hemp concrete wall manufactured by spraying

Hemp concrete is a non-load bearing material. It is used in association with a framework that can be steel-, concrete- or wood-framework. Usually, hemp concrete walls are coated on both sides but hemp concrete can occasionally be naked on the indoor side. The studied wall meets the practices encountered for sprayed wall (figure 1). Once the wood-framework is erected, hemp concrete is manufactured by spraying onto plywood formwork. The lime-based binder and plant particles are dry-mixed (22 kg of hemp shiv for 44 kg of lime-based binder). The water is added during projection at the nozzle of the spear. This spraying method is well-adapted to the construction buildings that do not exceed approximately 6 m in height. Two types of coating are used: a sand-lime coating (for indoor and outdoor) and a hemp-lime coating (for indoor only). The coating is applied manually with a trowel.

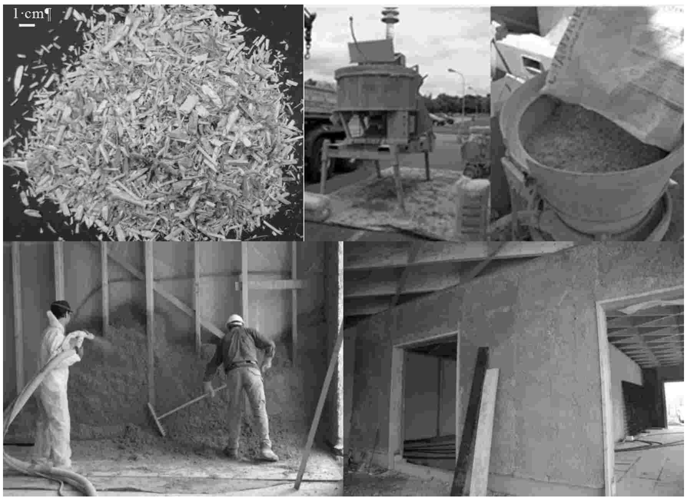

Figure 1. Hemp concrete Spaying Method: the mixer / lime and vegetable particles mixing / spraying.

3 Methodology

3.1 Functional Unit

The functional unit is defined with respect to the definition of the ISO 14040 standards [4][5]. Hemp concrete is considered as an insulation product, hence the thermal resistance R, measured in $m^2.K/W$, is a meaningful value in order to define the functional unit.

The functional unit studied in this paper was defined per square meter. Wall thickness was defined in order to conform to the French thermal regulation (RT2005) that sets the higher value of the heat transfer coefficient to 0.36 $W/m^2/K$. The wood used for the structure was included in the functional unit. The wood frame was not considered as a thermal bridge as its thermal conductivity is similar to that of hemp concrete. So, the functional unit ensures the function of a bearing wall and its thermal resistance is 2.78

m².K/W for a wall thickness of 27 cm (2 cm for the outdoor coating, 24 cm for hemp concrete and 1 cm for the indoor coating) (figure 2). For the base case, the coating was made of sand and lime.

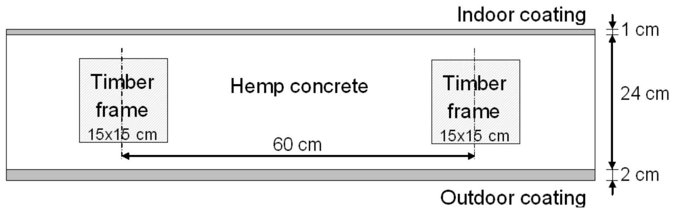

Figure 2. Cross view of the wall

The typical lifespan of the wall was assumed to be equal to 100 years, taking into account an adequate renewal of coatings (every 50 years for the indoor side and every 33 years for the outdoor side).

A sensitivity analysis was performed on the thickness of hemp concrete, on the kind of indoor coating (sand-lime vs. hemp-lime) and on the number of the renewals of coatings.

3.2 Elementary fluxes

Elementary fluxes (table 1) are defined as the quantities required for the system to satisfy the functions defined by the functional unit. The formulation of the hemp concrete was given by our industrial partner. The quantity of timber frame was calculated by including vertical structure, lintels, jambs, etc., that are traditionally found in wood construction. Globally, timber frame represents 20 kg of wood per square meter of wall.

Table 1: Elementary fluxes reliable to the functional unit (kg/FU)

Raw material	Hempshiv	Binder	Water	Timber frame	Sand
Hemp concrete (24 cm)	0.204	0.450	0.670	0.200	0.000
Outdoor coating (2 cm)	0.000	0.021	0.143	0.000	0.114
Indoor sand-lime coating (1 cm)	0.000	0.011	0.071	0.000	0.057
Indoor hemp-lime coating (1 cm)	0.011	0.071	0.052	0.000	0.000

3.3 Inventory method and data

The study has a cradle-to-grave perspective. The life cycle starts with the raw production and finishes with the disposal of the material at the end-of-life (figure 3). The considered phases used to estimate the environmental impacts in this Life Cycle Analysis are given bellow.

The extraction and production of raw materials (binder, shiv), including their transport from the production site to the company is described. Another phase explains hemp concrete implementation through a spraying process. The lifespan takes into account the carbonation of the binder and the renewal of coatings. At the end-of-life, the hemp concrete is disposed of, only the transport towards the landfill is taken into account.

Some assumptions were the same for all the phases:

- Environmental impacts generated by infrastructures were not taken into account. The production and transport of the machines needed for raw material production were excluded.

- Electricity used in the process was assumed to be produced in France and the impacts were given by the FD P 01-015 issue [26].

- The raw material packaging and its impacts were neglected and waste from the various life cycle stages were not taken into account.

- Data were extracted from the ECOINVENT database [12].

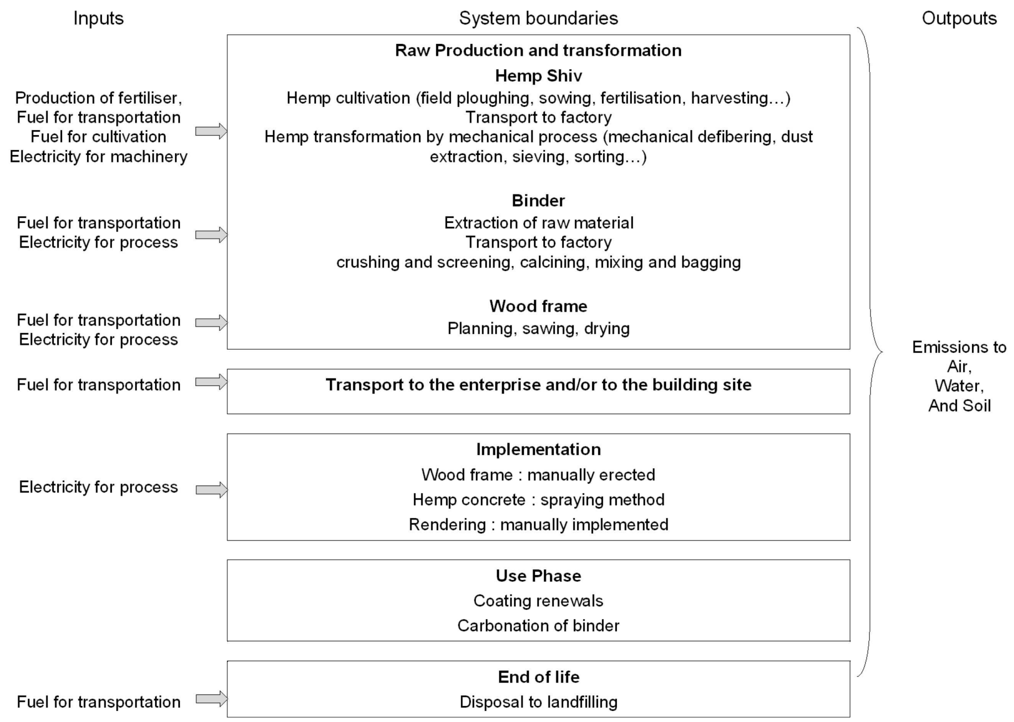

Figure 3. Life cycle of the hemp concrete wall

3.3.1 Hemp

Concerning hemp production, variable agricultural practices may occur. Also, the French average values for hemp production were taken into account by assuming good farming practices with respect to fertiliser and pesticide consumption [24][27][29]. An average production of hemp of approximately 8 t/ha was considered. This stage includes fertiliser production and its transport from the production site to the farm. The emissions due to the fertilisers used in fields are: Ammonia (NH_3) volatilised in the atmosphere (0.02 kg/kg of nitrogen supplied), nitrates (NO_3) emitted in surface water by leaching (40 kg/ha), nitrous oxide (NO_2) emitted in the air (0.0125 kg / kg of nitrogen supplied) and phosphates (PO_4^{3-}) discharged in surface water (0.01 kg /kg of phosphorus supplied). The production and use of fuel for hemp cultivation was included in the study [29].

The production and transport of seeds are not included in this study. The agronomical interest of hemp cultivation was not evaluated, though this plant needs neither insecticide nor fungicide treatments.

Hemp production is not mainly allocated to the construction sector and is rather oriented towards fibre production. Hence, an allocation was used to account for co-production of fibre, shiv and seed. The impacts were distributed on the products through a mass ratio. In most cases, the hempseed accounts for a negligible fraction of total hemp production and is not considered, 40% is considered as fibres and 60% is considered as shiv used in construction.

The assessment used to describe the production of shiv takes into account the average value of the three major French producers (LCDA, PDM industrie and Eurochanvre) [24]. As for the hemp, the production of shiv involves an allocation of the impacts. The production ratio in mass is 25% of fibres, 60% of shiv and 15% of powder. All these products are valorised industrially. The phase includes *(i)* the impacts and emissions due to electric energy consumption for the separation of shiv and fibres, *(ii)* the impacts and emissions due to the transport of hemp straw from the farm to the production site. The distance is about 300 km. Road transport is performed by a 24-ton truck loaded with 20 tons of hemp.

During the growth of hemp, the carbon is sequestered by photosynthesis. The amount of carbon dioxide required to create one kilogram of dry material is equal to 1.7 kg [22]. This was allocated as negative emission of carbon dioxide. .

3.3.2 Binder

The lime-based binder is made of 75% of hydrated lime (98% Cao), 15 % of hydraulic binder and 10 % of pozzolanic binder. The binder production includes the extraction of raw materials, transport from the extraction site to the transformation site, transformation, mixing and bagging. During the transformation process, the calcination of limestone (calcium carbonate) converts it into quicklime (carbon oxide) and releases carbon dioxide. The quicklime is then hydrated to turn oxides into dioxide ($Ca(OH)_2$). The amount of carbon dioxide released during calcination is of 594 g per kg of lime. Hydraulic binder is made from argillaceous limestone with impurities. In addition to calcium hydroxide, the calcination of limestone also forms calcium silicates, the amount of carbon dioxid released is 178.2 g per kilogram of hydraulic binder. The data related to the production of hydrated lime are taken from the French union of lime producers. They are representative of 90% of the French production of lime. The data related to the production of hydraulic binder are from the technical association of the hydraulic binder industry. They correspond to a cement of type CEM I. Finally, the overall production phase of the lime-based binder releases 778 g of carbon dioxide per kilogram of binder.

3.3.3 Wood

The wood used was produced and transformed in France. Wood transformation takes into account an electric consumption of 0.09 kWh per kg of wood for planing, 0.031 kWh per kg of wood for sawing and 0.6 kWh per kg of wood for drying. Timber frames were not treated. The distance between the production and the transformation sites is about 80 km. The sequestration of carbon by the wood is calculated considering 49.4 % of carbon in dry wood [30]. This leads to 1.787 kg CO_2/kg of wood and was taken into account as negative emission. Nevertheless, this value may depend on the end-of-life of the material.

3.3.4 Implementation, use phase and end-of-life

The raw materials were transported from the production site to the construction site in a 24-ton truck. The distances were approximately 800 km for the binder, 80 km for the wood and 300 km for the hemp shiv.

The implementation scenario included the energy needed for mixing the binder and the shiv and the energy needed for the projection.

The use phase scenario took coating renewal into account. The first coating was taken into account during the production phase. During the considered lifetime (100 years), the indoor coating is renewed once, whereas the outdoor one is renewed twice. A sensitivity analysis was performed with various renewal scenarios.

During the lifetime, the binder carbonation induces carbon sequestration. As the lifetime of the wall is long (100 years), the carbonation is assumed to be achieved all over the wall. The portlandite $Ca(OH)_2$ takes up carbon dioxide CO_2 to obtain $CaCO_3$ and release H_2O. The maximal quantity of carbon dioxide that can be re-absorbed is equal to the quantity released during the calcination. It is assumed that only the portlandite carbonates, and that the rate of portlandite in the binder is 100 % for the hydrated lime and 60 % for the hydraulic binder. Thus the carbonation of hydrated lime takes up 594 g of carbon dioxide per kilogram of lime while the carbonation of hydraulic binder takes up 106.9 g of CO_2 per kilogram of hydraulic binder.

At the end-of-life, all of the hemp concrete binder is carbonated. Additionally, the low thickness of the coatings induced achievement of carbonation within the coating's lifetime.

The end-of-life of hemp concrete is not well known. Actually, this is quite a new material. Its recycling seems possible but is not yet developed. So, landfilling is the most common used practice. At the end-of-life, materials are thus disposed of. A distance of 20 km from the building site to the landfill was considered. Only the transport towards the landfill was taken into account. It is considered that there is no decomposition of the material, and thus there are no greenhouse gas emissions.

3.4 Environmental indicators and analysis

Following the French standards NF P 01-010 [7], the results are given as 9 environmental indicators. (*i*) Primary energy demand (MJ/FU),(*ii*) water consumption (l/FU) and (*iii*) climate change (kg CO_2 equivalent /FU) are the most commonly used.

Atmospheric impacts are also accounted through (i*v*) Atmospheric acidification (kg SO_2 equivalent/FU), (*v*) photochemical ozone (kg ethylene equivalent/FU) and (*vi*) air pollution (m^3/FU). The air pollution indicator is expressed in m^3 of air required to dilute emissions of the product based on the limits for classified installations for environmental protection (method of the critical volume).

The impacts on water are expressed as (*vii*) water pollution (m^3/FU) and (*viii*) eutrophication (kg $(PO_4)^{3-}$/FU). This water pollution factor is expressed in m^3 of water required to dilute emissions of the product based on the regulation limits of registered environmental protection facilities (critical volume method). Eutrophication characterizes the imbalance resulting from excessive intake of nutrients, nitrogen, carbon and phosphorus in water.

(*ix*) The depletion of resources (kg equivalent of antimony/FU) is taken into account. Each resource is weighted by a coefficient corresponding to an index of scarcity. By convention, antimony has a unity value. A value greater than one means that the resource is scarcer than antimony. The resources whose coefficient is lower than 0.001 are considered non-exhaustible.

4 Results and discussion

4.1 Base case

The results are first presented according to the following phases: production of materials required to construct the wall, transport of materials from production site to construction site, implementation, use phase and end-of-life. A production phase analysis is then performed. Results are next detailed from a climate change point of view. Finally, the base case is compared to usual walls.

Table 2 gives the environmental indicators calculated in the base case and figure 4 shows the contribution of each phase for each indicator, with the exception of the climate change indicator, detailed in figure 6. Raw material production causes the largest contribution to environmental impact, with values over 75% for all the environmental indicators, with the exception of photochemical ozone that reaches only 50% of the impact. Material transport is the second contributor. Among environmental indicators, photochemical ozone is the highest, reaching 50%. It is linked to fuel consumption and emission of pollutants to the air. Conversely, transport has a low impact on water consumption and water pollution. The use phase is the least significant contributor to environmental impacts with between 5 and 15% of total impact. This result is mainly due to the renewal of the coatings that involves primary raw materials and water. Finally, implementation has a negligible impact because the energy consumption for mixing and spraying the hemp concrete is low by comparison with the energy needed for the production of the materials. Similarly, the impacts of the end-of-life are low because they are only linked to transport to a landfill.

Table 2. Environmental indicators linked to the functional unit

	Raw production for the wall	Transport	Implementation	Use Phase	End-of-life	Total
Energy raw consumption MJ/FU	4.267	0.343	0.399	0.384	0.017	5.410
Exhaustion of resources kg antinomy eq. /FU	2.74E-03	1.62E-04	4.61E-05	1.10E-04	7.98E-06	3.06E-03
Water consumption l/FU	2.50	0.03	0.08	0.41	0.00	3.02
Photochemical ozone kg eqethylene/FU	4.02E-05	3.62E-05	1.27E-06	2.11E-06	1.78E-06	8.15E-05
Climate change kg CO_2 eq./FU	0.152	0.027	0.003	-0.200	0.001	-0.016
Atmospheric acidification kg SO_2 eq./FU	1.06E-03	2.25E-04	1.85E-05	7.75E-05	1.10E-05	1.40E-03
Air pollution m^3 /FU	13.572	2.804	0.193	1.282	0.138	17.989
Water pollution m^3 /FU	0.602	0.001	0.001	0.087	0.000	0.691
Eutrophication kg $(PO_4)^{3-}$	1.82E-03	4.95E-04	4.15E-05	1.24E-04	2.43E-05	2.51E-03

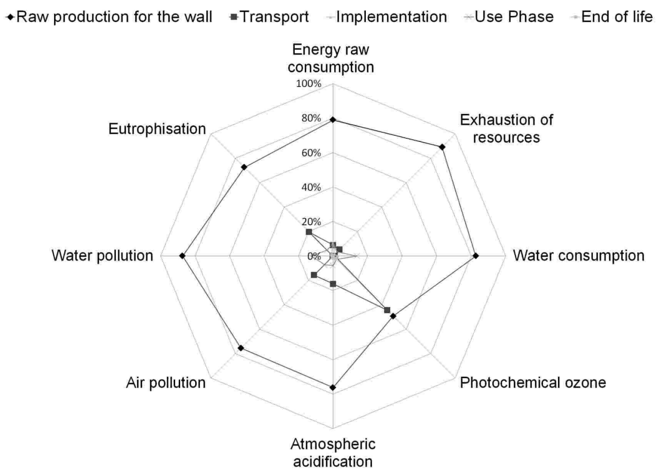

Figure 4. Contribution of Production, Transport, Implementation, Use phase and end-of-life to environmental impact

Thus, in order to more precisely analyse the production phase, figure 5 gives the contribution of each component of the wall: wood, coatings and hemp concrete. For this last, the contributions of binder and hemp shiv are detailed.

Among the various materials used, the binder shows the greatest impacts (49% of primary energy, 68% of water consumption and 47% of air pollution). Indeed, binder production requires high-temperature cooking (900 to 1000°C for the lime). The binder has also the greatest impact on water consumption due to the hydrated lime manufacturing process. This product is obtained by hydration of quicklime, requiring large volumes of water. Air pollution due to the binder is linked to the cooking that emits fumes due to the combustion of fossil energy.

The wood is the second contributor to environmental impact, with 37% of primary energy demand and 28% of the air pollution. It is the third contributor to water consumption (13%). Energy consumption is mainly due to drying during the production process. It should be reminded that the energy used is electricity and that a characterisation factor of 3.048 is used for electricity in Europe (1 MWh of final energy = 3.048 MWh of primary energy). Air pollution comes mainly from fuel consumption for the transport from forest to factory.

The coatings are the second contributors to water consumption, while they show only a slight impact on primary energy demand and air pollution (6%). Actually, the formulation of coatings requires a high quantity of water. Moreover, the coatings are mainly made of sand and are thick, so they embed little binder and hence little energy.

Finally, hemp shiv is the third significant contributor to primary energy demand and air pollution (resp. 8% and 19%). This comes from the fuel consumption of agricultural machinery and from transport. Their impact on water consumption is negligible (1%).

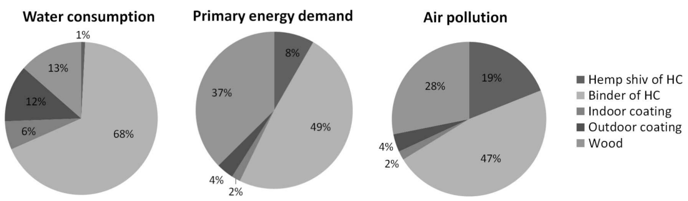

Figure 5. Distribution of production impacts between the different materials

The environmental impact on climate change takes into account the emitted greenhouse gases (figure 6). Production and transport have the greatest emissions. The production value is a balance of CO_2 emission and sequestration detailed below (figure 7). During the use phase, hemp concrete and coating binders take up carbon dioxide through the carbonation process. Moreover, there is nearly no impact on climate change as no material rotting is considered during landfilling. Finally, the global balance of the climate change indicator is favourable thanks to photosynthesis and carbonation.

Figure 7 details global emissions and carbon sequestration for each component of the wall. Hemp shiv gives negative CO_2 balance. Carbon sequestration from photosynthesis is much higher than emissions due to agricultural and industrial processes. Conversely, wood has a positive balance because the process (planning, sawing, drying, etc.) induces higher emissions than photosynthesis allows sequestration. The binder shows the highest indicator due to the high energy needed during the process.

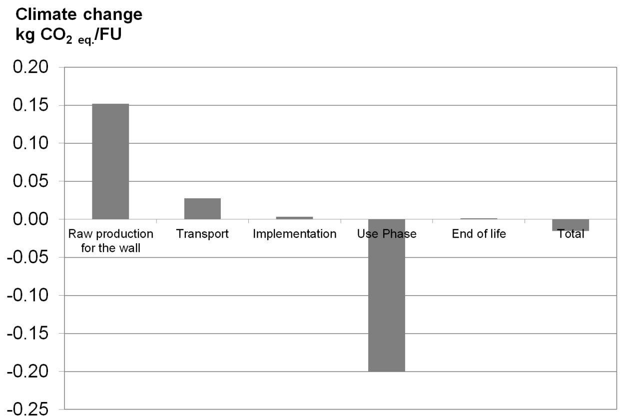

Figure 6. Impact on climate change for the different phases

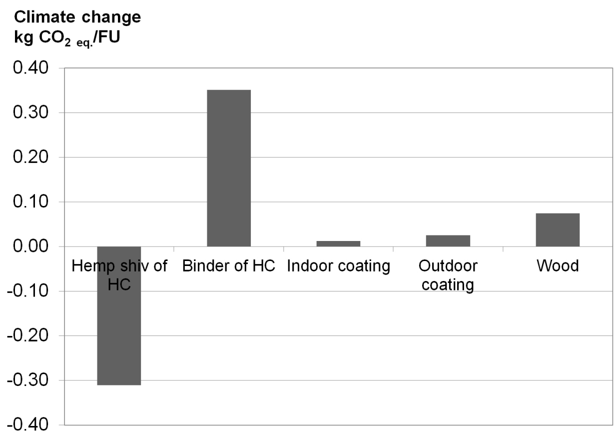

Figure 7.Detail of impact on climate change during production phase

These results were compared to traditional building products: a concrete block wall insulated with mineral wool and a brick wall. Even though these walls do not have exactly the same functional unit as the studied hemp concrete wall, they are used for the same practice in France as bearing and insulating walls. Thus, at wall scale, these systems can be compared with hemp concrete wall.

The data for these walls were obtained from the INIES database [31]. The concrete block wall is insulated with mineral wool and shows a thermal resistance equal to 2.37 $m^2.K/W$. The indoor side of this wall is covered with a gypsum board included in the functional unit. The outdoor rendering is excluded from the LCA. The lifetime of this wall is 50 years. The brick wall has a thermal resistance of 3.01 $m^2.K/W$. Its rendering is excluded. Its lifetime is 150 years and no renewal is taken into account. In all cases, the LCA includes production, transport, implementation and end-of-life. For the concrete block, the carbonation during the lifespan and end-of-life is taken into account. Lastly, the exclusion of rendering from the Environmental Product Declarations of concrete block wall and of brick wall leads to underestimation of their environmental impacts.

Figure 8 compares the environmental impacts of the three walls. The results are normalised to the ones of hemp concrete.

For the depletion of resources and the atmospheric acidification indicators, the results are similar for the three walls.

For the water consumption and water pollution indicators, the value is the lowest for the brick wall. Actually, the consumption of water is mainly due to the production of the brick that needs a small quantity of water. Moreover, this wall is implemented with narrow joints that requires less water than mortar joints. From a water pollution point of view, the factory does not emit process water in the outdoor environment, except for the vapour from the drying and cooking of brick.

For primary energy demand, the brick shows the highest impact mainly due to the production phase. The energy used for the production is provided from waste recycling to generate energy. Thus, only the transport of waste is accounted for primary energy consumption. For the concrete blocks, there is also an energy recovery from waste for the production of cement.

For emissions in the atmospheric air, the concrete block has the highest impact while the hemp concrete has the lowest one. These emissions are mainly due to the production process and the transport. The main discrepancy between the products appears on climate change. The hemp concrete wall exhibits lower impacts than the other building products, mainly due to carbon sequestration and carbonation.

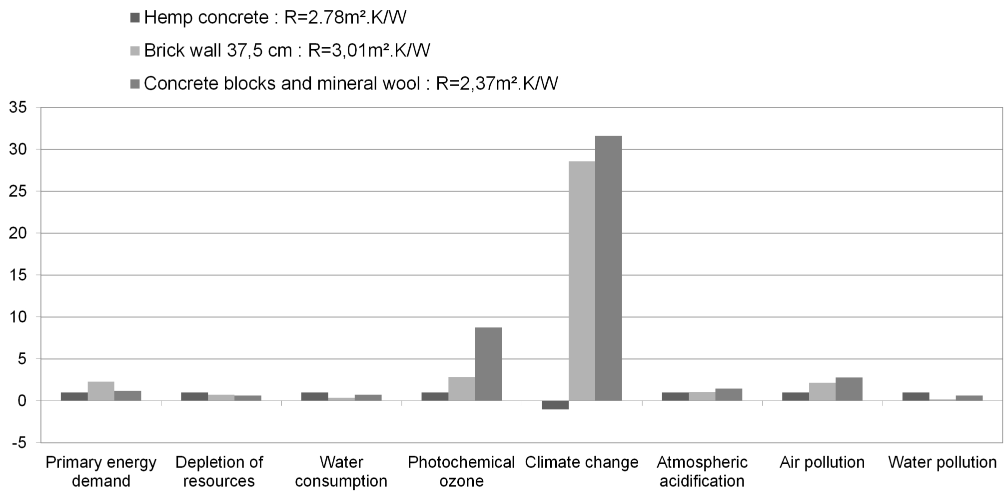

Figure 8. Environmental impacts of different building materials normalised by the results obtained for hemp concrete

4.2 Effect of wall thickness on environmental impact

The sensitivity of hemp concrete thickness was studied between 0.20 and 0.40 m. The coatings and wood framework remain unchanged. The increase in thickness induces higher thermal resistance (from 2.32 to 4.32 m².K/W) that reduces the thermal requirements of buildings. This positive effect cannot be taken into account here as the LCA was performed at the wall level.

Figure 9 gives the variation of environmental indicators (with the exception of the climate change indicator – figure 10) versus hemp concrete thickness. The results are normalised to the base case. Logically, the indicators vary in a linear fashion versus hemp concrete thickness. This thickness, however, impacts the various indicators unequally. A very slight effect was observed on water consumption (less than 1% between 0.24 and 0.40 m) due to the small amount needed for the hemp concrete mixture. The most impacted indicator is water pollution (64% increase between 0.24 m and 0.40

m). Raw energy consumption also increases significantly (approximately 40% between 0.24 m and 0.40 m). These indicators are mainly impacted by the quantity of binder that increases with thickness.

Figure 10 gives the variation of the climate change indicator versus wall thickness. This indicator decreases with wall thickness. For a 20 cm thickness, the indicator is positive because CO_2 uptake is lower than emissions. The balance becomes zero for a thickness equal to 0.22 m. Then, for higher thicknesses, the climate change indicator is favourable. This variation highlights the effects of carbon sequestration by hemp and of binder carbonation.

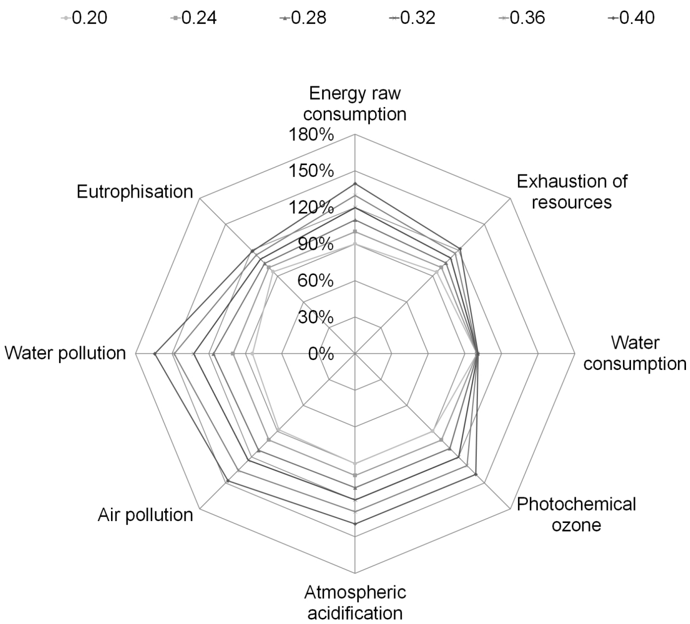

Figure 9. Effect of hemp concrete thickness on environmental indicators (normalised to the base case)

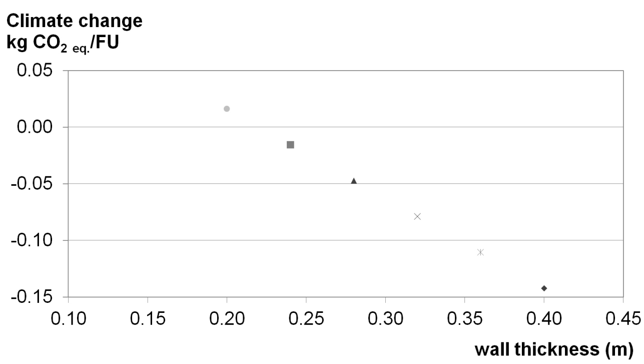

Figure 10. Effect of hemp concrete thickness on climate change indicator

4.3 Effect of coating renewal on environmental impacts

Coating renewal mainly depends on their deterioration and appearance. The effect of various numbers of renewals is presented in figures 11 and 12. The case where there is no indoor coating is also studied as it can be encountered for appearance or acoustical reasons.

Figure 11 gives the results normalised to the base case. The variation of all the indicators is lower than 10%. The effect is more pronounced for the renewal of outdoor coating due to its thickness. When there is no indoor coating, all the indicators decrease slightly (from 2 to 6%). Finally, coating renewal has no significant effect on the environmental indicators presented on figure 11.

From a climate change indicator point of view however (figure 12), the effect of the coating scenario is more pronounced. When there is no indoor coating, the indicator is better than for the base case. Actually, the saving of raw materials (and associated emissions) has a larger effect than the reduction of carbonation. Moreover, in general terms, an increase in the number of renewals increases environmental impacts. Beyond a given number of renewals, the climate change indicator becomes positive. The environmental benefits of such material are thus reduced.

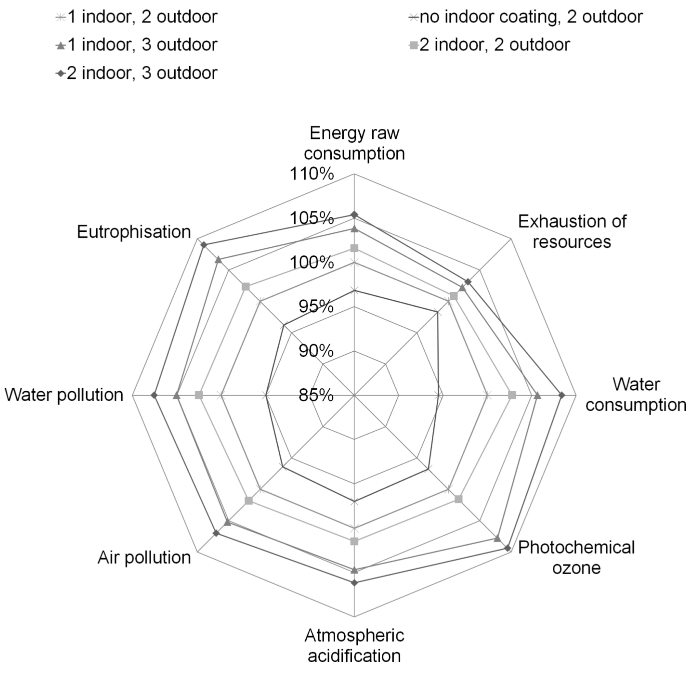

Figure 11. Effect of coating on environmental impacts – several renewals or no indoor coating

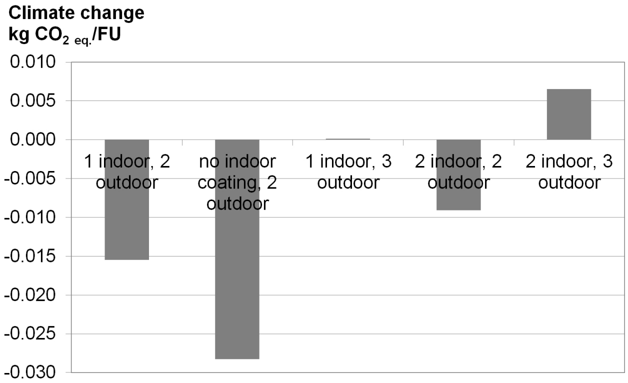

Figure 12.Effect of coating on climate change indicator – several renewals or no indoor coating

4.4 Effect of composition of coating on environmental impacts

Several kinds of indoor coatings are traditionally used with hemp concrete; among them sand-lime and hemp-lime coatings are the most frequently encountered. Figure 13 compares the environmental impacts of sand-lime and hemp-lime coatings (with normalisation to the base case = sand-lime).

For all the indicators, the hemp-lime coating is more impacting than sand-lime, as its composition involves much more binder (table 1). The most impacted indicators concern water pollution and climate change. Actually, the production of lime induces a high level of water pollution, greater energy consumption and high CO_2 emissions. Also, the favourable balance of the wall for the climate change indicator is half that obtained with the sand-lime coating (note that this indicator is negative and normalised to the base case).

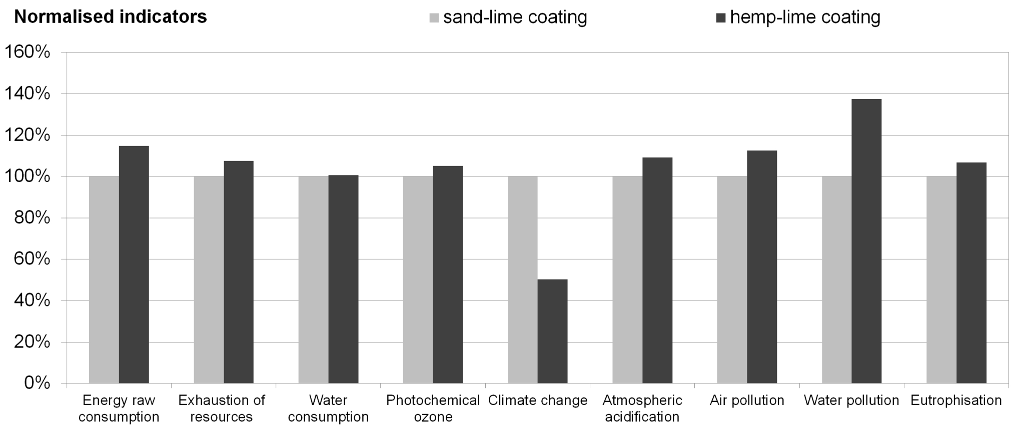

Figure 13.Effect of coating composition on climate change indicator

5 CONCLUSIONS

This study dealt with the LCA of a hemp concrete wall including wood framework, indoor and outdoor coatings.

The results show that the production of raw materials is the most impacting phase, mainly due to binder production. The balance of the climate change indicator is favourable as CO_2 uptake by photosynthesis and carbonation is higher than emissions. Moreover, compared to usual walls, hemp concrete appears as relevant. This underlines the high environmental quality of such walls.

A sensitivity analysis of the thickness of hemp concrete was performed. The increase in thickness improves the climate change indicator but also increases the other environmental indicators at the wall level. However, this also improves the thermal resistance of the wall and may reduce the energy needs of the building during the use phase. This would lead to a reduction in the building's global impacts.

Coating renewals impact the environmental indicator slightly, as long as there are not too many. By comparing sand-lime and hemp-lime coatings, it appears that the hemp-lime coating has a greater impact as it embeds more binder.

Finally, hemp concrete appears to be an environmentally friendly material. This quality could be improved by reducing the binder impact. Moreover, investigations should be continued by using these data to perform a life cycle analysis on a whole building.

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6 References

[1] Heijungs R., Huppes G.,Guinée J.B., Life cycle assessment and sustainability analysis of products, materials and technologies. Toward a scientific framework for sustainability life cycle analysis, Polymer Degradation and Stability, 95, pp 422-428, 2010.

[2]Xu X., Jayaraman K., Morin C., Pecqueux N., Life cycle assessment of wood-fibre-reinforced polypropylene composites, journal of materials processing technology, 198, pp 168-177, 2008.

[3] Lee J.J., O'Callaghan P., Allen A., Critical review of life cycle analysis and assessment techniques and their application to commercial activities, resources, conservation and recycling, 13, pp 37-56, 1995.

[4] ISO 14040, Environmental management – Life Cycle Assessment - Principles and Framework, 2006.

[5] ISO 14044, Environmental management – Life Cycle Assessment – Requirements and guidelines, 2006.

[6] EN 15804, Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products, 2012.

[7] Norme NF P 01-010. Qualité environnementale des produits de constructions: Déclaration environnementale et sanitaire des produits de construction.

[8] Trusty W.B., Introducing assessment tools classification system, Advanced building newsletter #25. Ottawa, Canada: Royal Architecture Institute of Canada, 2000.

[9]Basbagill J., Flager F., Lepech M., Fischer M., Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts, Building and Environment, 60, pp 81-92, 2013.

[10] Rossi B., Marique A.-F., Glaumann M., Reiter S., Life-cycle assessment of residential buildings in three different European locations, basic toll, Building and Environment, 51, pp 395-401, 2012.

[11]Rossi B., Marique A.-F., Reiter S., Life-cycle assessment of residential buildings in three different European locations, case study, Building and Environment, 51, pp 402-407, 2012.

[12] ECOINVENT CENTER, Ecoinvent 1996, Dübendorf: Swiss Centre for life-cycle inventories, 1996.

[13], BEES database <http:// ws680.nist.gov/bees>

[14], Luxembourg construction portal < www.crtib.li>

[15]GaBi LCA database<http://www.gabi-software.com/databases/>

[16] Verbeck G. and Hens H., Life cycle inventory of buildings: a calculation method, Building and Environment, 45, pp 1037-1041, 2010.

[17] Nässén J., Hedenus F., Karlsson S., Holmberg J., Concret vs. Wood in buildings – An energy system approach, Building and Environment, 51, pp 361-369, 2012.

[18] Ramesh T., Prakash R.,Shukla KK., Life cycle energy analysis of buildings: an overview, Energy and Buildings, 42, pp 1592-1600, 2010.

[19] Van OoteeghemK., Xu L., The life-cycle assessment of a single-storey retail building in Canada, Building and Environment, 49, pp 212-226, 2012.

[20] Monteiro H. and Freire F., Life-cycle assessment of a house with alternative exterior walls: Comparison of three impact assessment methods, Energy en Buildings, 47, pp 572-583, 2012.

[21] Frenette C. D., Bulle C., Beauregard R., Salenikovich A., Derome D., Using life cycle assessment to derive an environmental index for light-frame wood wall assemblies, Building and Environment, 45, pp 2111-2122, 2010.

[22] Bio-aggregate-based Building Materials, Applications to Hemp Concrete, edited by Amziane S. and Arnaud L., ISTE Ltd and John Wiley & Sons, Inc, 2013.

[23] Collet F., Chamoin J., Prétot S., Lanos C., Comparison of the hygricbehaviour of three hemp concretes, Energy and Buildings, 62, pp 294-303, 2013.

[24] Boutin M.P., Flamin C., Quinton S., Gosse G., Lille I, Etude des caractéristiques environnementale du chanvre par l'analyse de son cycle de vie, Paris, Ministère de l'agriculture et de la pêche.

[25] Ip K, and Miller A., Life cycle greenhouse gas emissions of hemp-lime wall constructions in the UK, Resources, Conservation and recycling, 69, pp 1-9, 2012.

[26] FD P 01-015 2006 Qualité environnementale des produits de construction - Fascicule de données énergie et transport, 2006.

[27] Hayo M.G. Van der Werf, 2004 Life cycle analysis of field production of fibrehemp,the effect or production practices on environmental impacts. Kluwer AcademicPublishers.

[28] ITC 2010, Institut technique du chanvre, expert data, 2010.

[29] IDEMAT 2001. Delft University of Technology, 2001

[30] Werner F., Althaus H.J., Künniger T., Richter K., Jungbluth N., Life cycle inventories of wood as fuel and construction material, Ecoinvent report n°9, Dübendorf, december 2003.

[31]<http://www.inies.fr/>